Multi-Year Program Plan

Solid-State Lighting
Research and Development
Portfolio

Draft Section 4.0:
Technology Research and Development Plan

FY’08-FY’12

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4.0 Technology Research and Development Plan

The U.S. Department of Energy supports domestic research, development, demonstration, and commercialization activities related to SSL to fulfill its objective of advancing energy-efficient technologies. The Department's SSL R&D Portfolio focuses on meeting specific technological goals, as outlined in this document, that will ultimately result in commercial products that are significantly more energy-efficient than conventional light sources.

Improving the efficiency and decreasing the cost of SSL will have a large contribution towards DOE's goal of a net-zero energy building (ZEB). Lighting constitutes approximately 12 percent of residential building energy consumption and 25 percent of commercial building energy consumption. This electricity consumption figure does not include the additional loads due to the heat generated by lighting, which is estimated to be up to 40 percent in a typical "stock" building. Further technology and cost improvements and market acceptance of SSL technologies will dramatically reduce lighting energy consumption, and thereby the total energy consumption, of residential and commercial buildings by 2025.[1]

A part of the Department's mission, working through a government-industry partnership, is to facilitate new markets for high-efficiency, general illumination products that will enhance the quality of the illuminated environment as well as save energy. Over the next few years, SSL sources will expand their presence in the general illumination market, replacing some of today's lighting technologies. The Department's R&D activities will work to ensure that U.S. companies remain competitive suppliers of the next generation of lighting technology in this new paradigm.

This chapter describes the objectives and work plan for future R&D activities under the SSL program for the next 7 years, with some general observations to 2025. Actual accomplishments will result in changes to the plan over this time period which will be reflected in future revisions.

The next section sets forth working definitions of the various components of a solid-state lighting luminaire in order to provide a common language for describing and reporting on the R&D progress.

4.1. Components of the SSL Luminaire[2]

Subsequent sections of this multiyear plan describe both LED and OLED white-light general-illumination luminaires. Understanding each component of a luminaire and its contribution to overall luminaire efficiency helps to highlight the opportunities for

[1] 2006 Building Energy Data Book, U.S. Department of Energy, Office of Planning, Budget and Analysis, Energy Efficiency and Renewable Energy. Prepared by D&R International, Ltd., September 2006. Hereafter, BED.

[2] To be consistent with terms used in the SSL Testing and Energy Star Programs, "luminaire" is used here to describe the entire solid state lighting product

energy-efficiency improvements and thereby to define priorities for the Department's SSL R&D Portfolio.

4.1.1. Components of LED Luminaires

As solid state lighting has evolved, a number of product configurations have appeared in the market. While definitions are still in flux, they are beginning to solidify so that we can identify two essential levels of product based on whether or not they include a driver and a number of terms in each level:

Component level (no power source or driver)

- LED Device refers to the packaged light-emitting semiconductor chip or die including the mounting substrate, encapsulant, phosphor if applicable, and electrical connections.

- LED Array. Several LED chips may be packaged together on a common substrate or wiring board in order to increase total light output or improve the spectrum.

- LED Module. This term is new and refers to an LED packaged with additional components such as thermal, mechanical, or electrical interfaces

Subassemblies and Systems (including a driver)

- LED Lamp refers to an assembly with a standardized base consisting of an LED device integrated with an LED Driver. Such assemblies are generally intended as replacement products for conventional light bulbs, although this situation may evolve over time should standardized bases specific to LEDs come into being.

- LED Light Engine is a term in fairly wide use now, and refers to a subsystem of a luminaire that includes one or more LED Devices, arrays or modules, an LED Driver, an integral heat sink, and appropriate mechanical interfaces. It is intended to be a building block for an LED Luminaire, below.

- LED Luminaire refers to the complete lighting unit, intended to be directly connected to an electrical branch circuit. It consists of a light source, as above, and driver along with parts to distribute the light and to connect, position, and protect the light source.

In the above definitions, the term LED Driver means a power source with integral control circuitry designed to meet the specific needs of an LED Device, Array, or Module. The driver converts line voltage to appropriate power and current for the device and may also provide sensing of and corrections for shifts in color or intensity that occur over the life of the product or due to temperature variations. Other special features, such as dimming controls, may also be included.

Figure 4-1, below, illustrates a few of these definitions.

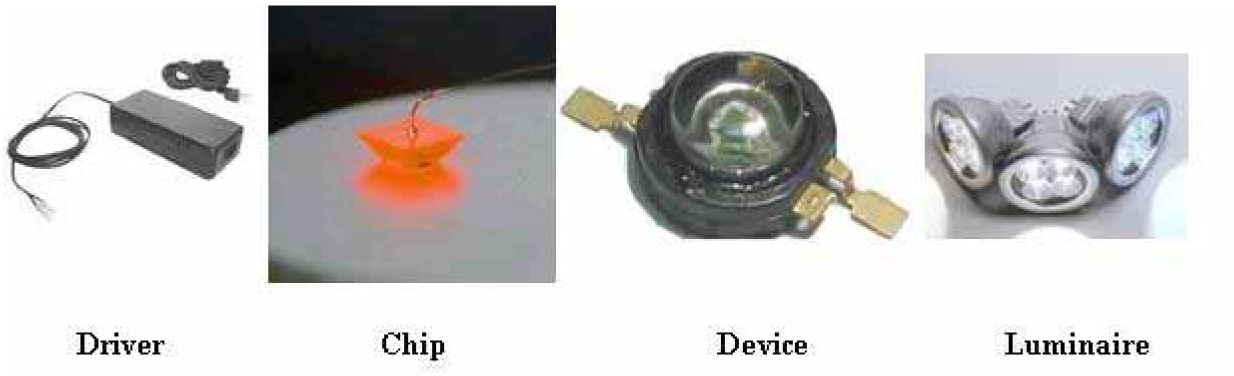

Figure 4-1: Photos of LED Luminaire Components
Sources: Lumileds, Color Kinetics.

4.1.2. Components of OLED Luminaires

Because of the nature of the OLEDs, the number of product configurations can be described below in simpler terms. At the component level, there is the OLED device and at the system level, there is the OLED luminaire.

- <u>OLED Device</u> refers to the layers of materials, including a set of charge transporting and emissive layers (made of organic materials) that correspond to those of the basic LED chip. Other layers provide encapsulation, electrical connection and packaging. Because OLEDs are a diffuse light sources, large areas are needed for general illumination applications. Therefore the electrodes of an OLED must be relatively complex in order to spread current out over a large area efficiently. A number of specific OLED device structures are possible, and a few are mentioned below.

- <u>OLED Luminaire</u> refers to the complete lighting unit, intended to be directly connected to an electrical branch circuit. It consists of the OLED device, driver, and fixture. The OLED driver converts line voltage to appropriate power and current for the device. The OLED fixture provides for mounting and mechanical support for the device, interconnection with the driver, and diffusion or direction of the light from the OLED device to the task. Because OLEDs are more diffuse light sources, less complicated fixtures may be possible relative to LEDs or conventional light sources.

Geometries that emit downwards through a transparent substrate or upward from a reflective substrate are currently being considered for OLEDs. The simple planar structure shown in Figure 4-2 below displays an OLED which emits downward through a transparent substrate. These structures typically employ a reflective, metal cathode.

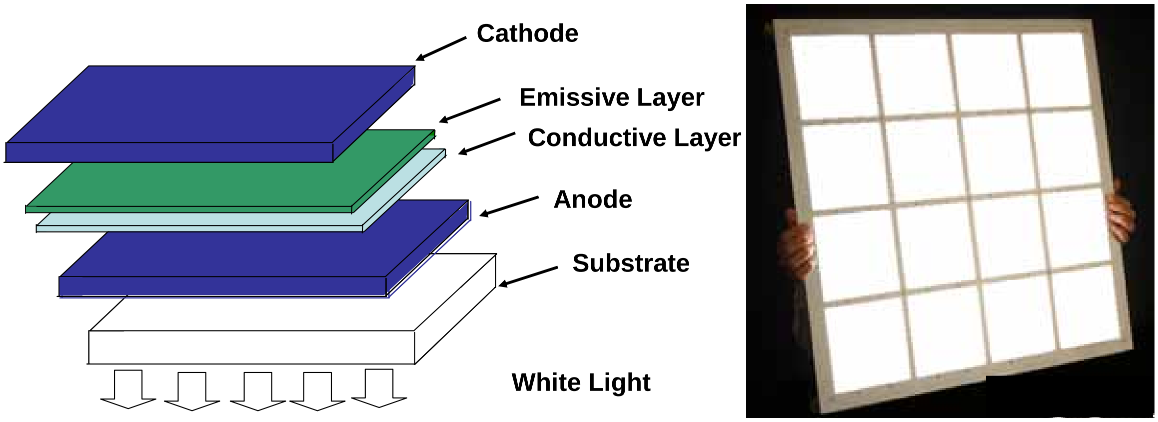

Figure 4-2: Diagram/Photo of OLED Panel
Photo source: General Electric.

It is also possible to manufacture an OLED with a highly transparent cathode (typically with up to 80% transmission across the visible spectral region). These structures can emit upward from a reflective substrate, such as a reflective metal foil, or can be entirely transparent devices. Figure 4-3 displays an entirely transparent OLED employing a transparent substrate and cathode.

Figure 4-3: Photo of a Transparent OLED Lighting Tile
Photo source: OSRAM Opto

4.2. Current Technology Status and Areas of Improvement

Significant progress has been made in LEDs over the past year and several viable and efficient luminaire products have reached the market. More are expected in the coming year. LED device technology successfully met the first milestone set by DOE's multi-year plan and appears to be ahead of schedule for the next one. As a result, some LEDs are now more efficient than incandescent sources and are approaching parity with CFLs. More work will be necessary to assure that luminaires and power conditioners do not excessively degrade the performance of the devices. More work will also be necessary to reach efficiencies that can compete with linear fluorescent lamps. OLED performance lags behind LEDs, as might be expected from that technology's later start. There are essentially no viable OLED products for general illumination available today; however, there is reason to believe that they are not too far off.

To further define the relationship among the components of luminaires and to highlight relative opportunities for efficiency improvements, one can identify various elements of power efficiency, both electrical and optical, within the SSL device and for the luminaire as a whole. These losses and consequent opportunities for LED and OLED luminaires are apparent in the several figures that follow (Figure 4-4, Figure 4-5, and Figure 4-6). Generally, the losses identified result from the conversion of energy, either electrical or optical depending on the stage, into heat. However, the efficiency of converting optical radiated power into useful light (lumens) is derived from the optical responsiveness of the human eye. This source of inefficiency (the *spectral* or *optical* "efficacy" of the light) is essentially spectral filtering of light by the eye that has already been radiated by the SSL luminaire.

The electrical *luminaire* efficacy, a key metric for the DOE SSL program, is the ratio of *useful* light power radiated (visible lumens) to the electrical power (watts) applied to the *luminaire*. The electrical *device* efficacy refers to the ratio of lumens out of the *device* to the power applied to the device; so it does not include the driver or fixture efficiencies. This technology plan forecasts both device efficacy and luminaire efficacy improvements. It is important to keep in mind that it is the luminaire efficacy that determines the actual energy savings.

Opportunities for improvement of the device include: reducing electrical and optical losses in the device; improving the efficiency of conversion of electrons into photons (IQE); the extraction of those photons from the material (extraction efficiency); and tailoring the spectrum of the radiated light to increase the eye response. Tailoring of the spectrum to the eye response is constrained by the need to provide light of appropriate color quality (correlated color temperature (CCT) and color rendering index (CRI)).

The following sections compare the current typical efficiency values for the individual luminaire elements to a set of suggested program goals for LED and OLED technologies. These are consensus numbers, developed over a series of weekly consultations with members of the NGLIA. It is important to realize there may be significantly different allocations of loss for any specific design, which may also result in an efficient luminaire. This allocation of typical current efficiency values and targets serves as a useful guide for identifying the opportunities for improvement (*i.e.*, those components with the greatest differences between current and target values). It is *not,* however*,* the program's intention to impede novel developments which use a different allocation of losses that result in a better overall luminaire performance.

For consistency, OLED efficiencies throughout this chapter are reported at a fixed brightness (1,000 cd/m^2) and output (>500 lm). LEDs are reported for a fixed drive current (350 mA) and area (1mm^2). These values are simply used to compare efficiency levels and set targets. Using these reference values is not intended to imply that they are ideal or even the most desirable drive current densities or brightness levels.

4.2.1. Light Emitting Diodes

As described in Section 2.3.4, white-light LED luminaires are typically based on one of two common approaches:

(a) discrete color-mixing and
(b) phosphor-conversion LEDs (pc-LEDs).

Color-mixing LED

Figure 4-4 presents a diagram of a color-mixing LED luminaire. The percentage efficiencies in the diagram next to each component indicate the typical performance in 2007 and targets that will satisfy the goals of the program. Therefore, this diagram depicts the present inefficiencies of the various luminaire components and the headroom for improvement. For purposes of comparing various experimental results, this diagram, as well as the next one, assumes a target correlated color temperature of 4100°K (the equivalent CCT of a cool white fluorescent lamp), and a CRI of at least 80. Other combinations may provide acceptable light for particular market needs, but may then be inappropriate for the targets indicated. Currently available 2007 products typically have color temperatures in the range of 4100-6500°K, and usually a lower CRI.[3] The 2007 typical numbers reflect these less than optimal parameters, and therefore may overstate our current capability. For simplicity, Figure 4-4 depicts RGB color-mixing using LEDs that are not phosphor converted. However, other options are possible. Some manufacturers mix phosphor converted white LEDs with monochromatic red or amber LEDs to achieve a warm white color.

Over the course of the program, performance improvements will make possible the manufacturing of devices with lower color temperature and better CRIs without seriously degrading the efficiency. Achieving the efficiency targets identified in Figure 4-4 will require more efficient emitters (particularly in the green area of the spectrum) and other improvements elsewhere in the luminaire.

[3] The DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) supports the testing of a wide, representative array of SSL products available for general illumination, using test procedures currently under development by standards organizations. More information is available at: http://www.netl.doe.gov/ssl/comm_testing.htm

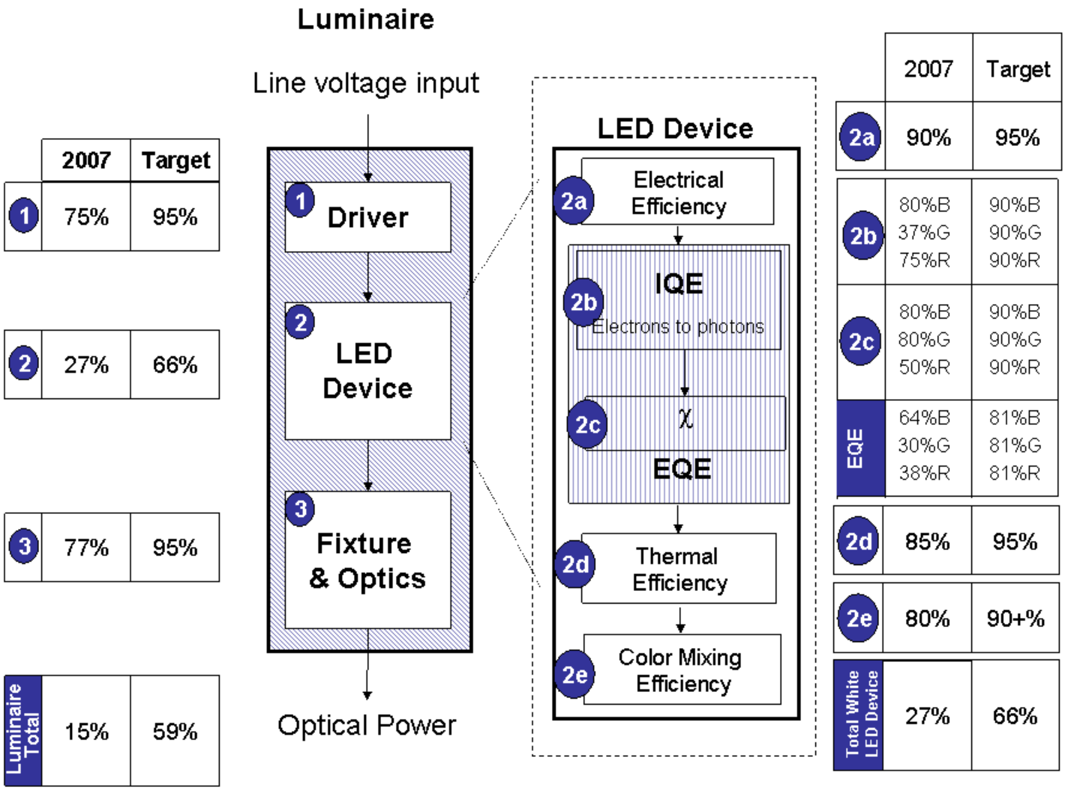

Figure 4-4:Color-Mixing LED- Current and Target Luminaire Efficiencies for Steady State Operation

Source: NGLIA LED Technical Committee, Fall 2007
Note: The target assumes a CCT of 4100K and CRI of 80; Current CCT: 4100-6500K, CRI: 75

The following definitions provide some clarification on the efficiency values presented in the figures and for the project objectives over time.

> Driver efficiency represents the efficiency of the electronics in converting input power from 120V alternating current to low voltage direct current as well as any controls needed to adjust for changes in conditions (e.g. temperature or age) so as to maintain brightness and color.

> Device efficiency, There are several components of the device electrical efficacy that are shown on the right in Figure 4-4 and also defined below. The output of the “LED device” in this figure is useful lumens; that is, the spectral effects are not included within the “device” box.

Fixture and optics efficiency, η_{fo}, is the ratio of the lumens emitted by the luminaire to the lumens emitted by the LED device in thermal equilibrium. Losses in this component of the luminaire include optical losses. (For purposes of this illustration, spectral effects in the fixture and optics are ignored, although this may not always be appropriate.)

Considering the device portion of the luminaire, the power efficiency is the ratio of electrical input from the driver (i.e., applied to the device) to the optical power out (irrespective of the spectrum of that output). As such, device power efficiency excludes driver losses. The device *efficacy* is the product of the power efficiency of the device and the spectral or optical efficacy due to the human eye response. Elements of the device power efficiency are:

Electrical efficiency, η_V, accounts for the ohmic losses within the device and the loss of any charge carriers that do not arrive at the active region of the device. The forward voltage should be as low as possible in order to achieve the maximum number of charge carriers into the device active region. When resistive losses are low, the voltage is essentially the breakdown voltage which is approximately the bandgap energy divided by the electronic charge. Ohmic losses in the LED material and electrode injection barriers add to the forward voltage. This efficiency also includes any loss of charge carriers that occurs away from the active region of the device.

Internal quantum efficiency, IQE, is the ratio of the photons emitted from the active region of the semiconductor chip to the number of electrons *injected into* the active region.

Extraction efficiency, χ, is the ratio of photons emitted from the encapsulated chip into air to the photons generated in the active region. This includes the effect of power reflected back into the chip because of index of refraction difference, but excludes losses related to phosphor conversion.

External quantum efficiency, EQE, is the ratio of extracted photons to injected electrons. It is the product of the internal quantum efficiency, IQE, and the extraction efficiency χ.[4]

[4] In practice, it is very difficult to separate the relative contributions of internal quantum efficiency and extraction efficiency to the overall external quantum efficiency. At the same time, it is useful to make the distinction when discussing the objectives of different research projects. At present, it is common for individual laboratories to compare measurements of different device configurations in order to estimate relative improvements. This makes it difficult to compare and use results from different labs, and so it would be worthwhile to try to develop some measurement standards for these parameters.

Thermal Efficiency is the ratio of the lumens emitted by the device in thermal equilibrium under continuous operation to the lumens emitted by the device at 25°C.[5]

Color-mixing efficiency, η_{color} , here refers to losses incurred while mixing the discrete colors in order to create white light (not the spectral efficacy, but just optical losses). Color-mixing could also occur in the fixture and optics, but for the purposes of Figure 4-4 is assumed to occur in the device.

The device-related parameters of the luminaire have the greatest headroom for improvement in the short term. For example, the internal quantum efficiencies (2b) of the chips range from 20% to 80%, depending on color. The ultimate goal is to raise the IQE to 90% across the visible spectrum, bringing the total device efficiency to 66%. As the LEDs become more efficient, there will necessarily be more emphasis on the other luminaire losses in order to maximize overall efficiency.

In this figure, the driver (1) has an efficiency of 75% in today's products. This driver efficiency is somewhat lower than that for a phosphor converting LED (see Figure 4-5) because the driver needs to produce different colors at different drive voltages with controllable intensities. The ultimate target for this component is to improve the efficiency to be greater than 95%. Likewise, there is considerable room for improvement of the fixture and optics. Currently, the color-mixing LED luminaire is approximately 15% efficient at converting electrical energy into visible white-light. If all targets are achieved, the LED device would have an efficiency of 66%, with an overall luminaire efficiency of 59%.

The device power efficiency (W_o/W_e) measures the energy of light emitted by the device divided by the electrical energy put into the device. This metric is independent of the spectrum of light emitted by the device. Electrical luminous efficacy (in lm/W_e)[6], on the other hand, measures of the amount of useful visible light out of a device per unit of electrical energy. The electrical luminous efficacy of the color-mixing LED device can be calculated by multiplying the device power efficiency by the *optical* or *spectral* luminous efficacy of radiation (LER). For blended LEDs, the LER is approximately 360 lm/W_o (exact value varies with the CRI and CCT for the particular design and the available wavelengths[7]). Using this conversion, the target for a color mixing LED device would be close to 237 lm/W_e (66% efficiency, above, multiplied by 360 lm/W_o). This would result in an overall luminaire efficacy, absent significant breakthroughs, of approximately 213 lm/W_e. These additional luminaire losses are the reason that the program includes tasks directed at fixture and driver efficiency as well as those

[5] Standard LED device measurements use single pulses of current to eliminate thermal affects, keeping the device at 25°C. In standard operation, however, the LED is driven under CW (continuous wave) conditions. Under these conditions, in thermal equilibrium the device operates a temperature higher than 25°C.

[6] The subscript "e" denotes electrical power into the device and "o" denotes optical power within the device. Unless otherwise stated, "efficacy" means electrical luminous efficacy.

[7]NIST has simulated an LER of 361 lm/W_o at a CRI of 97 and CCT of 3300K. (Ono, Y. "Color Rendering and Luminous Efficacy of White LED Spectra." Proc. SPIE 49th Annual Mtg., Conf. 5530 (2004).)

emphasizing the basic LED device, and also why the most energy-efficient installations of the future will have purpose-designed luminaires as opposed to simply retrofit lamps. These are "practical" figures based on the sources and technology that can be envisioned now. The electrical to optical power conversion efficiency could improve and the spectral luminous efficacy could also be higher, as much as 400 lm/W_o for a CRI of 80, if optimal wavelengths are available. This would yield a higher overall figure for lumens per watt.

Phosphor Converting LED

Figure 4-5 below, presents a diagram of a phosphor converting LED luminaire. The definitions for the various efficiencies are the same as listed for Figure 4-4, with additional definitions for phosphor efficiency and scattering efficiency:

> Phosphor efficiency, η_{phos}, the value given in 2e is given for current state of the art green-yellow phosphors necessary to create a simple white emitting device using a blue emitting LED. In order to improve the color quality of phosphor converted white devices while maintaining high efficiency it will be necessary to improve the phosphor efficiency of phosphors that emit in the red wavelengths and, possibly, the efficiency of phosphors that emit in the green to blue-green region of the spectrum. The phosphor efficiency includes the Stokes loss of the phosphor.
>
> Scattering efficiency is the ratio of the photons emitted from the LED device to the number of photons emitted from the semiconductor chip. This efficiency, relevant only to the phosphor converting LED in Figure 4-5, accounts for scattering losses in the phosphor and encapsulant of the device.

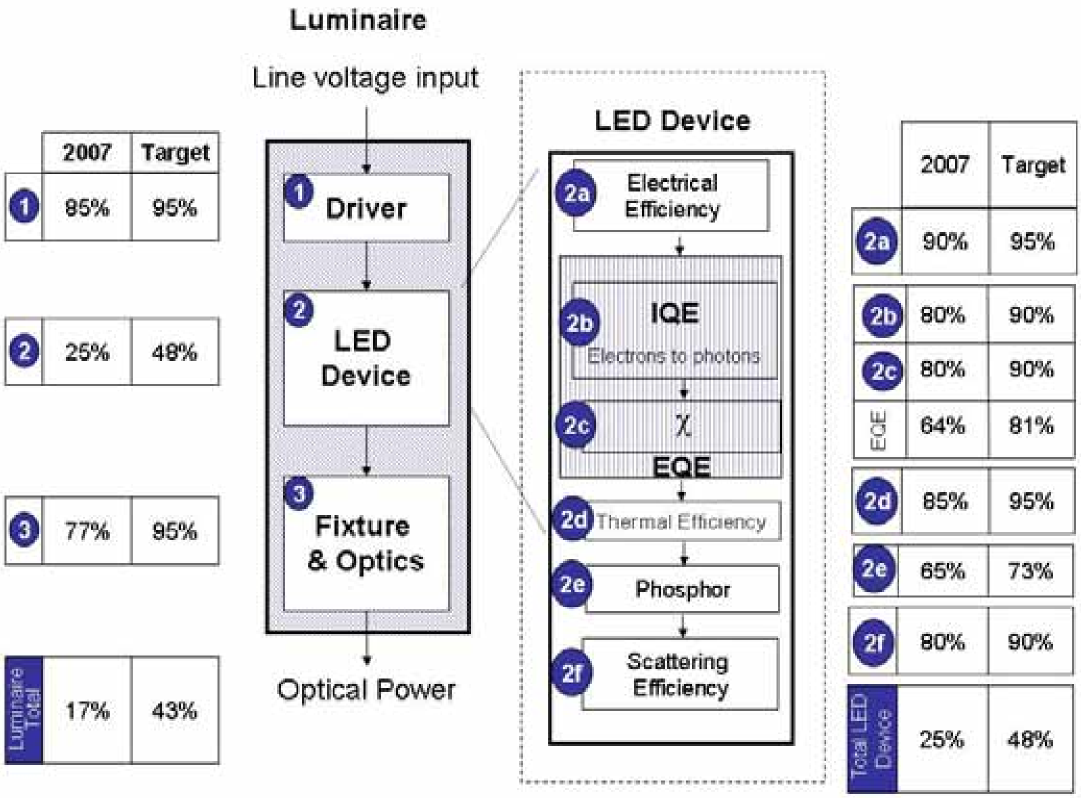

Figure 4-5: Phosphor Converting LED- Current and Target Luminaire Efficiencies for Steady State Operation

Source: NGLIA LED Technical Committee, Fall 2007
Note: The target assumes a CCT of 4100K and CRI of 80; Current CCT: 4100-6500K, CRI: 75
Note: The target for 2e includes the loss due to the Stokes shift (90% quantum yield times wavelength ratio); the value here is typical of a blue diode/yellow phosphor system.

In the above figure, Component 2a, the LED device electrical efficiency, has an efficiency of 90% for 2007 products (with available switching techniques). The ultimate target for this component is to improve the efficiency to greater than 95%. In comparison, other components of the luminaire have more room for efficiency improvements. For example, the extraction efficiency of the LED chip is currently 80%. The ultimate goal is to raise the extraction efficiency of the mounted, encapsulated chip to 90%.

The areas with the greatest headroom for improvement are the internal quantum efficiency (2b) and extraction efficiency (2c) of the LED chip, and the fixture and optics (3). Currently, the phosphor-converting LED luminaire is approximately 17% efficient at converting electrical energy into visible white-light. If all targets are reached, the LED device would have an efficiency of 48%, with a luminaire efficiency of 43%. Similarly to the color-mixing device, the electrical luminous efficacy (in lm/W_e) of the phosphor converting LED device can be calculated by multiplying the device power efficiency (W_o/W_e) by the *optical* luminous efficacy (useful light out (lm) divided by the optical power in (W_o)) of a phosphor. Similar to color-mixing LEDs, a practical target for a phosphor-converting LED luminaire is about 171 lm/W_e. Improving the phosphor efficiency and temperature performance could improve the efficacy even more.

4.2.2. Organic Light Emitting Diodes

Similarly, Figure 4-6 presents a diagram for an OLED luminaire and compares the current typical efficiency values for the individual system elements to a set of suggested program targets.

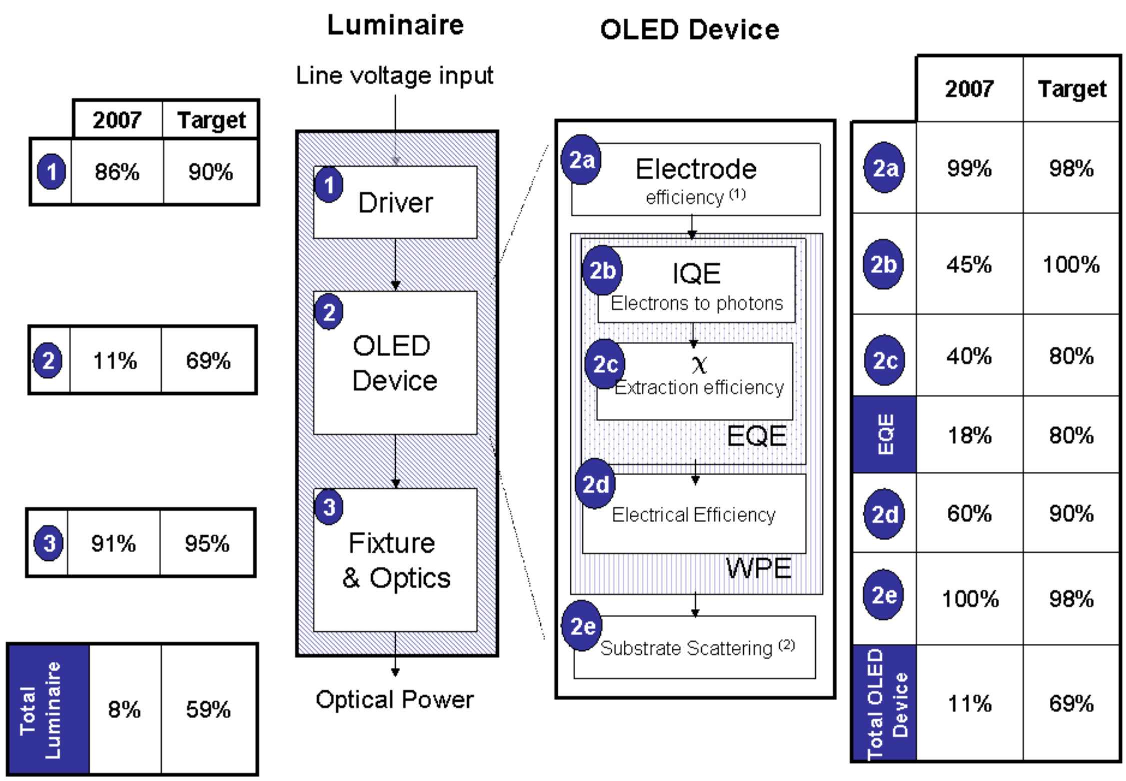

Figure 4-6: OLED Luminaire Efficiencies & Opportunities

(Assumptions for "Target" figures: CCT: 2700-4100K, CRI: 80, 1,000 cd/m2, total output ≥ 500 lm)

Note 1: Electrode loss is negligible for devices currently used for small displays but will be an issue for large area devices necessary for general illumination applications in the future.

Note 2: Includes substrate and electrode optical loss – negligible for glass and very thin electrodes but may be important for plastic or thicker electrodes

Source: NGLIA OLED Technical Committee, Fall 2007

While there is significant room for improvement in the active layers which comprise the device, considerable attention will have to be paid to the practicalities of OLED manufacturing. Early assembly technologies for OLEDs, which are focused on display applications, usually employ glass substrates with virtually no scattering loss. Transitioning to a flexible polymer substrate may be necessary to realize low cost manufacturing, but that may also reduce the device efficiency. The figure above estimates a target of 98% electrode efficiency, but this may be optimistic. Similarly, electrode design techniques may reduce losses in the conductors, but could also obstruct or impair portions of device emission, thus reducing overall device efficiency. Today, this is sometimes evidenced by dim regions on even a relatively small panel. There are electrode design techniques that can improve but not entirely eliminate electrode resistance, but it could become a significant issue as panel sizes increase. Thus, while this diagram shows very small source losses from these effects, as they can be in lab devices, a commercialized product with that level of loss may be difficult to achieve.

The external quantum efficiencies OLED layers can be relatively good for green (in contrast to the situation for LEDs) but are lower for blue and red, thus depressing the overall performance of white light. The goal is to achieve EQE values in the 80% range within the time period of this forecast. The same discussion with regards to the overall efficacy as outlined in the LED section applies here as well; lumens per optical watt depends on available wavelengths and efficiencies while the power efficiency depends on the other loss mechanisms.

Fixture efficiencies for OLEDs may also be relatively high when compared to conventional fixtures. Because OLEDs can be large area emitters, fixtures, to the extent that they are used to reduce glare, could almost be eliminated if the total lumen output of the OLED is distributed over a large enough area.

Keys to efficiency improvements in OLEDs continue to revolve around finding suitable stable materials with which to realize white light, with blue colors being the most difficult. Progress on efficiencies for OLEDs is nonetheless expected to be relatively rapid, as discussed in the next section. However, achieving efficiency gains alone will not be sufficient to reach viable commercial lighting products. The films must also be producible in large areas at low cost which highlights the importance of minimizing substrate and electrode losses, as noted above and in the figure, and may also limit materials choices.

4.3. SSL Performance Targets

With these improvement goals in mind, a projection of the performance of SSL devices was created in consultation with the NGLIA Technical Committee, a team of solid-state lighting experts, assuming adequate funding by both government and private industry. The authorization level for the SSL program is $25M for 20 years, which has not been achieved so far, but is still a reasonable estimate of the need. Appropriated funding has steadily increased over the life of the program (see Figure 3-1). Meeting these goals assumes that there are no unforeseen resource availability problems. Although the overall SSL program may be expected to continue until 2025 in order to achieve technologies capable of full market penetration, the OLED efficacy forecast in this section only projects performance to 2012 due to a lack of knowledge about the ultimate limit of this technology. However, a discussion of the performance of LEDs as well as the expected price of OLEDs up to the year 2025 is presented.

In order to capture the ultimate objectives of the SSL program which relate to *luminaire* efficacy or cost, objectives for luminaire performance are also included along with device performance objectives. It is important to note that the graphs are of device performance. Reaching the luminaire objectives will take longer, as shown by the luminaire efficacy values in Table 4-2. Innovative fixtures for LEDs can have a significant impact on overall efficacy. For example, device efficiencies (and operating lifetime) can be degraded by 30% or more when operating at full temperature at steady state in a luminaire. Although device efficiencies can be degraded in luminaires, SSL will still help DOE meet its Zero Energy Building (ZEB) goals by providing a luminaire that is more efficient than other lighting technologies. Accommodating both aesthetic and marketing considerations, while preserving the energy-saving advantages of solid state lighting is a challenge in commercializing this technology. Section 5.6 of the SSL MYPP discusses DOE's commercialization support plan.

4.3.1. Light Emitting Diodes

The performance of white LED devices depends on both the correlated color temperature (CCT) of the device and, to a lesser extent, on the color rendering index (CRI). While we cannot examine every case, we have shown efficacy projections for two choices: one for cooler CCT (4100K to 6500K), and the other for warmer CCT (2700K to 3500K). Because the majority of commercial products sold today are cool white products, forecasts for these products are more predictable. Therefore for the cool white case, projections are shown both for laboratory prototype LEDs, and for commercially available packaged LEDs. Experience suggests that a one and a half year lag between laboratory results and commercial product is fairly typical. Efficacy projections for warm white commercial LEDs are also given.

Figure 4-7 shows device efficacy improvement over time. Actual results through 2008 show that progress has been faster than was expected in the March 2007 projection. However, progress is not expected to continue at this rate over the next few years.

We are beginning to approach what are perceived to be the practical limits of efficacy as shown in Table 4-1. These limits depend on the choice of CCT and color quality demanded by the application. Apart from these more or less predictable limits, manufacturing and cost considerations may further reduce efficacies below their maxima. Based on our expected rates of improvements going forward, these maximum efficacies should be achieved in products between the years 2016 and 2020.

Table 4-1: Practical Maximum Device Efficacy for LEDs

Maximum Efficacy (lm/W)		
CCT	75 CRI	90 CRI
3000K	182	162
4100K	220	193
6500K	228	186

Source: NGLIA LED Technical Committee, Fall 2007

By 2013 the efficacy for high power cool white laboratory prototypes should reach 184 lm/W. Cool white commercial products should reach a level of approximately 172 lm/W by that time. By 2025, the projections approach the practical maximum efficacies for LEDs of 228 lm/W for cool white LEDs and 162 lm/W of warm white LEDs (with a CRI of 90). All projections assume a prototype with a "reasonable" device life.

A number of actual reported results for both high power and low power diodes are plotted, although these specific examples may not meet all of the criteria specified. Because many more low power diodes are required to make a useful light source, reported results between low and high power LEDs are not directly comparable. For example, although one can achieve a high efficacy light source using these low-power devices, there may be issues of higher assembly cost that need attention. While higher efficacy claims have been made, they cannot be compared unless all parameters are known.

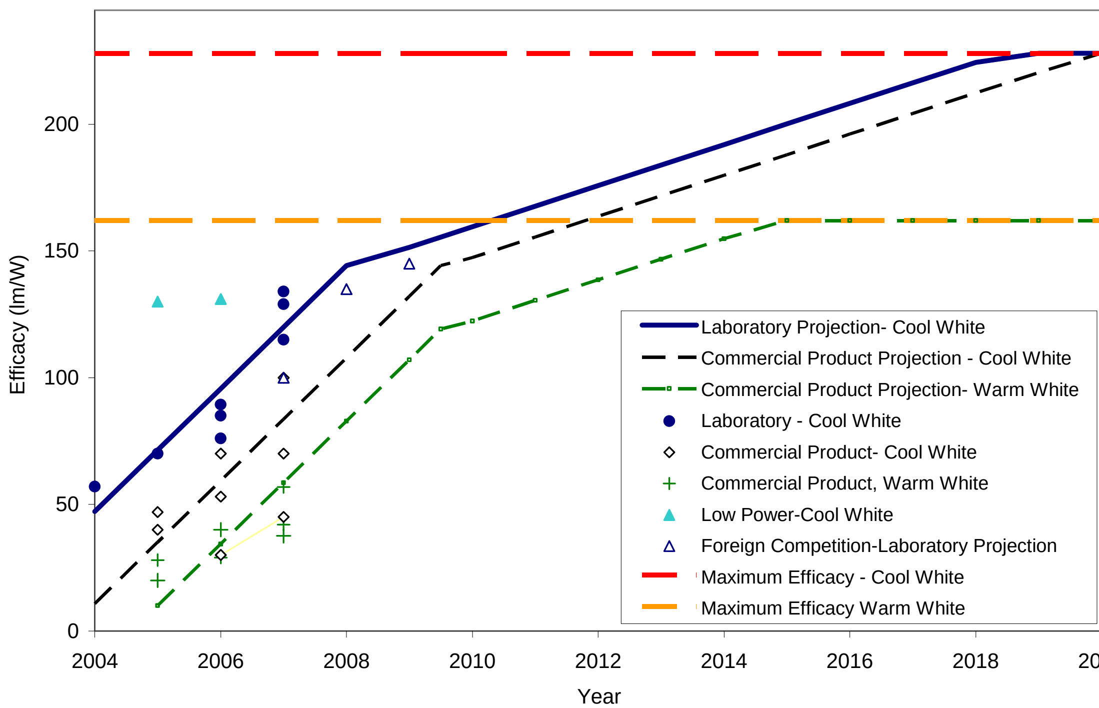

Figure 4-7: White Light LED Device Efficacy Targets, Laboratory and Commercial

Note:
1. Cool white efficacy projections assume CRI=70 → 80, CCT = 4100-6500°K,
2. Warm white efficacy projections assume CRI>85, CCT =2800-3500°K
3. All projections are for high-power diodes with a 350 ma drive current at 25°C, 1mm^2 chip size, device-level specification only (driver/luminaire not included), and reasonable device life.
4. Low power diodes shown have a 20 mA drive current.
5. The maximum efficacy values displayed in Table 4-1 for warm white and cool white are shown above as asymptotes.

Source: NGLIA LED Technical Committee and the Department of Energy, Fall 2007 and Press Releases

The cost estimates were also developed in consultation with the NGLIA Technical Committee, and represent the average purchase cost of a 3 watt white-light LED device driven at 350 mA (excluding driver or fixture costs). The projected original equipment manufacturer (OEM) device price, assuming the purchase of "reasonable volumes" (i.e. several thousands) and good market acceptance, is shown in Figure 4-8. By way of rough comparison, *lamp* prices for conventional technologies are shown on the same chart. The price decreases exponentially from approximately $35/klm in 2006 to $2/klm in 2015. Recent price reduction announcements seem to confirm the trend, at least in the near term.[8] Beyond 2015, price projections for LEDs will remain at or near $2/klm.

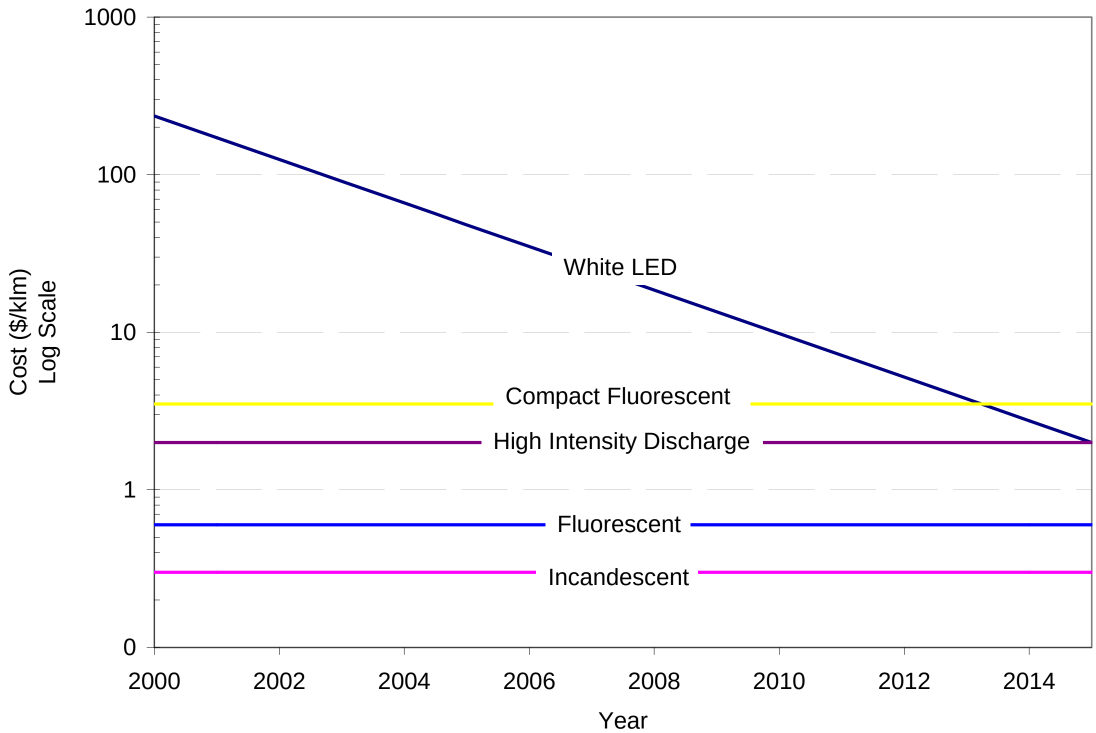

Figure 4-8: White Light LED Device Cost Projection (logarithmic scale)

Note: Price targets assume "reasonable volumes" (several 1000s), CRI=70 → 80,
CCT = 4100-6500K, and device-level specification only (i.e., driver/fixture not included)
Assumes 1-3 W white LED device, 13 W compact fluorescent lamp, 250 W metal halide lamp, 32 W T-8 linear fluorescent lamp, and 60 W A19 incandescent lamp with 2008 prices.
Source: NGLIA LED Technical Committee, Fall 2007

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[8] Typical lamp costs for conventional light sources listed in section 2.3.2 are also listed here for comparison: Incandescent Lamps (A19 60W), $0.30 per klm; Compact fluorescent lamp (13W), $3.50 per klm; Fluorescent Lamps (F32T8), $0.60 per klm; High-Intensity Discharge (250W MH), $2.00 per klm. It is important to note that to operate an LED device, a heat sink, fixture, and driver are required. Therefore the full price of an LED luminaire (~$100/klm in2008) is greater than that of the device ($25/klm in 2008). Furthermore, costs among light sources shown in Figure 4-8 are not directly comparable as these light sources may not need a driver, or heat sink to operate. It is also important to keep in mind that energy savings, replacement cost, and labor costs factor into a lamp's overall cost of ownership. LEDs are already cost competitive on that basis with certain incandescent products.

The device life, measured to 70% lumen maintenance[9], has increased steadily over the past few years and appears to be currently at its target of 50,000 hours. Although it appears that the majority of LEDs have reached the target of 50,000 hours, this has not been substantiated as yet by actual long term operating data. Methods for characterizing lifetime, especially as changes in materials or processes are introduced, will likely require accelerated aging tests which so far have not been established for LED technologies. This is an important area of work (and there is an identified task for it described in Section 4.5).

An average device life of 50,000 hours allows LED devices to last more than twice as long as conventional linear fluorescent lighting products, five times longer than compact fluorescent lamps, and fifty times longer than incandescent lighting products. This long life makes LEDs very competitive with conventional technologies on a "Cost of Light" basis (See Section 2.3.3). However, the total cost of ownership is not substantially affected by lifetimes greater than approximately 50,000 hours. LED products for niche/specialty applications could be developed with longer device life, upwards of 100,000 hours, by trading off with other performance parameters.

It is important to note that although the device lifetime may be 50,000 hours, the luminaire lifetime may be shorter. Bad luminaire design can shorten the life of an LED dramatically through overheating. Drivers may also limit the lifetime of an LED luminaire. Therefore improving the lifetime of the driver to equal or exceed that of the LED device and improving heat management within an LED luminaire are goals of the SSL program.

Table 4-2 presents a summary of the LED performance projections in tabular form.

[9] The device life stated above accounts for the lumen maintenance of the LED but does not account for other failure mechanisms.

Table 4-2: Summary of LED Device Performance Projections

Metric	2007	2010	2012	2015
Efficacy- Lab (lm/W)	120	160	176	200
Efficacy- Commercial Cool White (lm/W)	84	147	164	188
Efficacy- Commercial Warm White (lm/W)	59	122	139	163
OEM Device Price- Product ($/klm)	25	10	5	2

Note: 1. Efficacy projections for cool white devices assume CRI=70 → 80 and a CCT = 4100-6500°K, while efficacy projections for warm white devices assume CRI= >85 and a CCT of 2800-3500°K. All efficacy projections assume that devices are measured at 25°C.
2. All devices are assumed to have a 350 mA drive current, 1mm^2 chip size, device-level specification only (driver/fixture not included), and lifetime as stated in table.
3. Price targets assume "reasonable volumes" (several 1000s), CRI=70 → 80, Color temperature = 4100-6500K, and device-level specification only (driver/luminaire not included)
4. Device life is approximately 50,000 hrs, assuming 70% lumen maintenance, "1 Watt device," 350 mA drive current.
Source: NGLIA LED Technical Committee, Fall 2007

4.3.2. LEDs in Luminaires

As stated in section 4.2.1, the LED device is only one component of an LED luminaire. To understand the true performance metrics of a solid state lighting source, one must also take into account the efficiency of the driver, and the efficiency of the fixture. Provided below in Table 4-3 is luminaire performance projections to complement the device performance projections given in Table 4-2.

Table 4-3 assumes a linear progression over time from the current 2007 fixture and driver efficiency values to eventual fixture and driver efficiency 2015 program targets as given in section 4.1.1. Estimating the factors that affect the performance of an LED luminaire, it appears that a cool white luminaire in 2007 was capable of achieving 50 lm/W (although not all did so). By 2015 cool white luminaire efficacies should reach a capability of 161 lm/W. A projected efficacy for a warm white luminaire is not given here as it depends on the details of the light source design.

Table 4-3: Summary of LED Luminaire Performance Projections (at operating temperatures)

Metric	2007	2010	2012	2015
Device Efficacy-Commercial Cool White (lm/W, 25 degrees C)	84	147	164	188
Thermal Efficiency	85%	89%	91%	95%
Efficiency of Driver	85%	89%	91%	95%
Efficiency of Fixture	77%	84%	88%	95%
Resultant luminaire efficiency	59%	68%	75%	86%
Luminaire Efficacy-Commercial Cool White (lm/W)	47	97	121	161

Notes:
1. Efficacy projections for cool white luminaires assume CRI=70 → 80 and a CCT = 4100-6500°K. All projections assume a 350mA drive current, 1mm^2 chip size, reasonable device life and operating temperature.
2. Luminaire efficacies are obtained by multiplying the resultant luminaire efficiency by the device efficacy values.
Source: NGLIA LED Technical Committee, Fall 2007

4.3.3. Organic Light Emitting Diodes

In consultation with the NGLIA Technical Committee for general illumination, DOE developed price and performance projections for white light OLED devices operating in a CCT range from 2700-4100°K and a CRI of 80 or higher. Two projection estimates are shown: one for laboratory prototype OLEDs, and one for (future) commercially available OLEDs. Because it is difficult to obtain a highly efficient blue OLED emitter, similar projections for cooler CCT values will have lower efficiencies than their warmer CCT counterparts shown below. This is unlike LEDs where cooler CCT values are more efficient than their warmer CCT counterparts. Efficacy projections for OLEDs with a CRI of 90 or higher will also be slightly lower than projections shown.

Figure 4-9 (plotted on a logarithmic scale) predicts that the efficacy of laboratory prototypes will grow exponentially to exceed 150 lm/W by 2012. Based on new data, the NGLIA OLED technical committee has changed the efficacy projection to be more aggressive than in the 2007 Multi-Year Program Plan. As there are not yet any commercial OLED lighting products, the estimated efficacies for commercial products are not meaningful until 2009 and lag approximately three years behind the laboratory products. Projections above 150 lm/W would be speculative given our current understanding of the technology. Therefore, these projections are not shown.

These projections assume the CRI and CCT mentioned above and a luminance of 1,000 cd/m^2 and total output of at least 500 lumens. These projections apply to a white-light

OLED device "near" the blackbody curve (Δc_{xy}<0.01)[10], which may be a necessary criterion to market the products for various general illumination applications. A number of actual reported results are plotted next to the performance projections, although these specific examples may not meet all of the specified criteria.

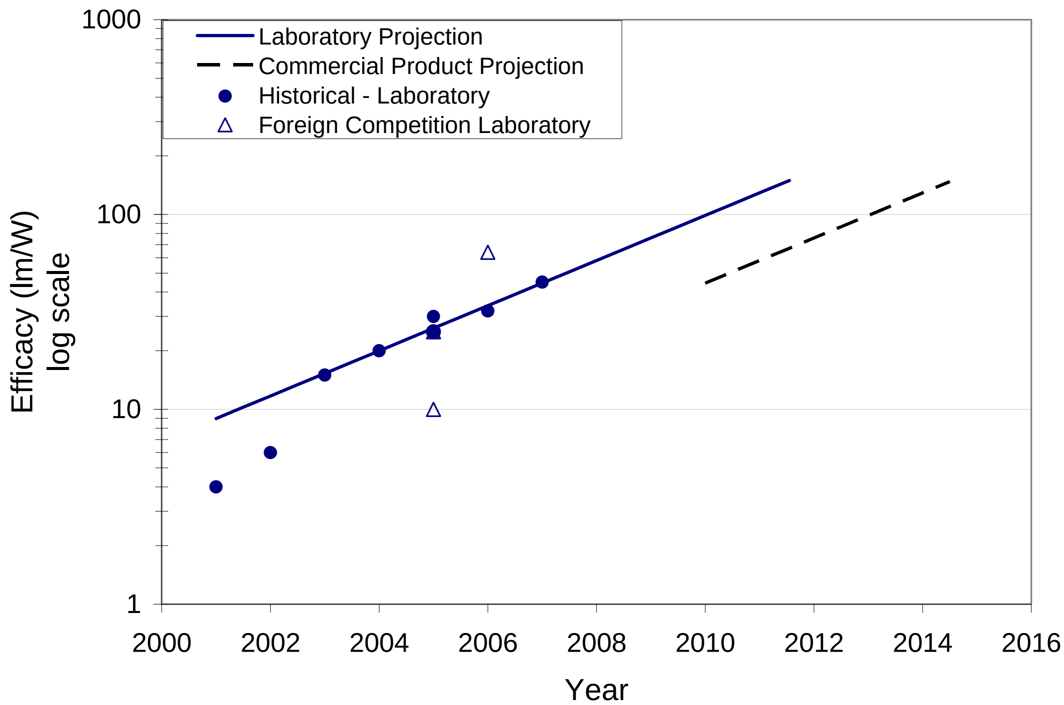


Figure 4-9: White Light OLED Device Efficacy Targets, Laboratory and Commercial

(On a logarithmic scale)

Note: Efficacy projections assume CRI > 80, CCT = 2700-4100°K ("near" blackbody curve (Δc_{xy} <0.01), lifetime > 1000 hrs, luminance of 1,000 cd/m^2, total output ≥ 500 lm, and device level specification only (driver/luminaire not included).
Source: Projections: NGLIA OLED Technical Committee, Fall 2007, Laboratory Points: Press Releases

Today, the efficacy of OLED devices lags behind LED devices, and there are no products on the market. However, researchers are optimistic and when the projections of commercial LEDs and OLEDs are compared (see Figure 4-10), the efficacy of OLED products approaches that of the LED products in the latter part of the current forecast.

[10] Δc_{xy} is the distance from the blackbody curve in C.I.E. color space.

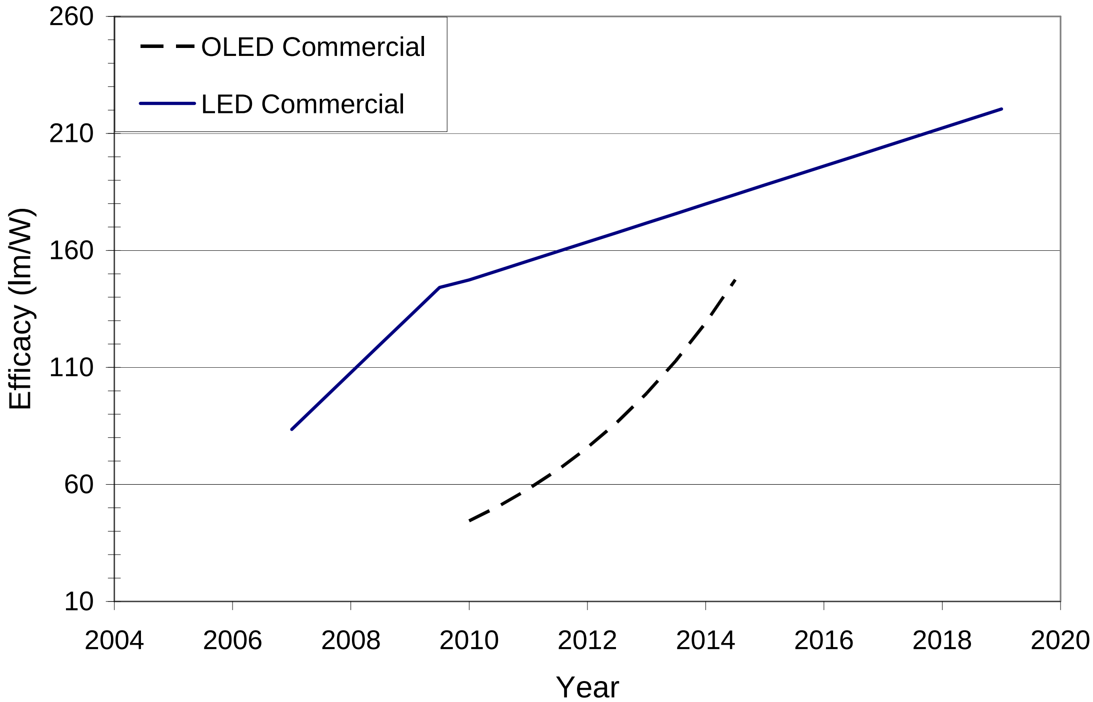


Figure 4-10: LED and OLED Device Efficacy Projections, Commercial

Source: NGLIA OLED Technical Committee and the Department of Energy, Fall 2007

Figure 4-10 presents the anticipated OEM price of commercially available white-light OLED devices (driver and fixture not included) for a luminance of 1,000 cd/m^2 and a total output of at least 500 lumens. Based on current costs of fabrication, we estimate that the 2009 OEM device price would be about $72/klm. The price is expected to fall to $10/klm by 2015, assuming reasonable volumes of tens of thousands. Prices of OLEDs may remain around $10/klm after 2015, although future price reductions are possible. The OEM device price, measured in \$/m^2 is approximately a factor of three greater than OLED device price when measured in $/klm for the assumed luminance. It is important to note that the price projections below are for OLED devices and not luminaires. Because an OLED driver and fixture may be less costly than that of a conventional lighting source, an OLED luminaire with a more expensive "device" may still be cost competitive with a conventional luminaire.

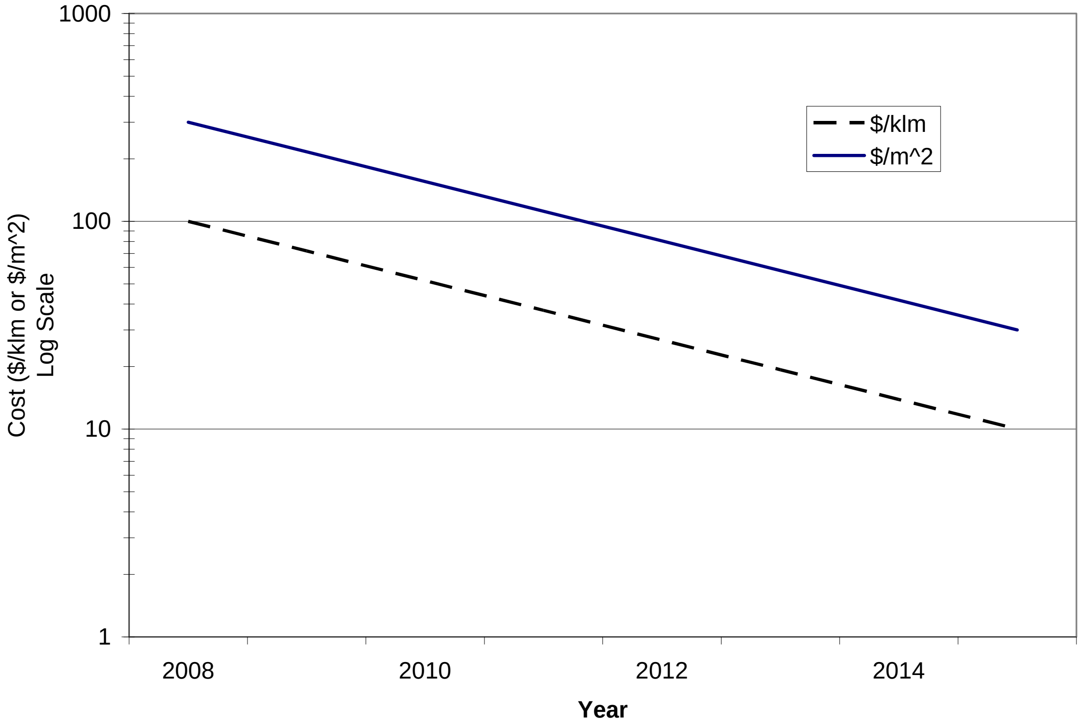


Figure 4-11: White Light OLED Device Price Targets, $/klm and $/m2
Note: Price targets are displayed on a logarithmic scale
Source: NGLIA OLED Technical Committee, Fall 2007

The device life for commercial products, defined as 70% lumen maintenance, is expected to increase linearly to a value of approximately 40,000 hours in 2015. Although 50% lumen maintenance is industry practice for evaluation of OLED displays, we use 70% lumen maintenance[11] in order to compare lifetimes with other lighting products.

Table 4-4 presents a summary of the OLED performance projections in tabular form. Lifetime projections below represent the lifetime of the device, not the entire luminaire. Because the driver may limit the lifetime of the OLED luminaire, improving the lifetime of the driver to at least equal that of the OLED device is a goal of the SSL program.

[11] Like LEDs, device lifetimes account for the lumen maintenance of the OLED but do not account for other failure mechanisms.

Table 4-4: Summary of OLED Device Performance Projections

Metric	2007	2009	2012	2015
Efficacy- Lab (lm/W)	44	76	150	150
Efficacy- Commercial (lm/W)	N/A	34	76	150
OEM Device Price- ($/klm)	N/A	72	27	10
OEM Device Price- ($/m^2)	N/A	216	80	30
Device Life- Commercial Product (1000 hours)	N/A	11	25	40

Notes:
1. Efficacy projections assume CRI = 80, CCT = 2700-4100°K ("near" blackbody curve (Δc_{xy}<0.01), luminance of 1,000 cd/m^2, total output ≥ 500 lm, and device level specification only (driver/luminaire not included)
2. OEM Price projections assume CRI = 80, luminance of 1,000 cd/m^2, total output ≥ 500 lm, and device level specification only (driver/luminaire not included)
3. Device life projections assume CRI = 80, 70% lumen maintenance, luminance of 1,000 cd/m^2, and total output ≥ 500 lm.
Source: NGLIA OLED Technical Committee, Fall 2007

4.3.4. OLEDs in Luminaires

The table below details a summary of the efficiency losses that occur when considering the entire OLED luminaire. Losses in the driver account for the majority of the efficiency degradation while losses in the fixture are assumed to be lower. In addition, OLEDs do not show significant thermal degradation loss, an effect that required the thermal efficiency component for LEDs shown in Table 4-3. Again, a linear improvement over time is assumed from current 2007 driver and fixture efficiency values to 2015 program targets as given in Figure 4-6. After taking into account all of the factors that affect the performance of an OLED luminaire and multiplying them by our original device efficacy projections, the 2009 OLED commercial luminaire efficacy status becomes 16 lm/W while the 2015 OLED commercial luminaire efficacy projection becomes 129 lm/W.

Table 4-5: Summary of OLED Luminaire Performance Projections

Metric	2009	2012	2015
Commercial Device Efficacy (lm/W) (Table 4-4)	34	76	150
Efficiency of Fixture	92%	93%	95%
Efficiency of Driver	87%	88%	90%
Total Efficiency from Device to Luminaire	80%	82%	86%
Resulting Luminaire Efficacy- Commercial Product (lm/W)	27	62	129

Notes:
1. Efficacy projections assume CRI = 80, CCT = 2700-4100°K ("near" blackbody curve ($\Delta c<0.01xy$), luminance of 1,000 cd/m^2, total output $\geq$ 500 lm, and device level specification only
Source: NGLIA OLED Technical Committee, Fall 2007.

4.4. Barriers

The following lists some of the technical, cost, and market barriers to LEDs and OLEDs. Overcoming these barriers is essential to the success of the SSL program.

1. Cost: The initial cost of light from LEDs and OLEDs is too high, particularly in comparison with conventional lighting technologies such as incandescent and fluorescent (see section 2.3.2 – 2.3.3). Since the lighting market has been strongly focused on low first costs, lifetime benefits notwithstanding, lower cost LED and OLED device and luminaire materials are needed, as well as low-cost, high-volume, reliable manufacturing methods.
2. Luminous Efficacy: As the primary measure of DOE's goal of improved energy efficiency, the luminous efficacy (lumens/watt) of LED and OLED luminaires still need improvement. Although the luminous efficacy of LED luminaires has surpassed that of the incandescent lamps, improvement is still needed to compete with other conventional lighting solutions. While laboratory experiments demonstrate that OLED devices can be competitively efficacious as compared to conventional technologies, no products are yet available.

3. Lifetime: The lifetime of LEDs and OLEDs is defined as the number of hours for which the luminaire maintains 70% of its initial lumen output. The lifetime target for the LED device has apparently been achieved. However, it is unclear whether this same lifetime target has been achieved by the LED luminaire. Potential premature failure due to high temperature operation remains a barrier to general deployment. OLED lifetimes for both devices and luminaires still require improvement.
4. Testing: The reported lumen output and efficacies of LED products in the market do not always match laboratory tests of performance. Improved and standardized testing protocols for performance metrics need to be developed. An important barrier appears to be a lack of understanding of the meaning of device specifications versus continuous operation in a luminaire on the part of designers.
5. Lumen Output: LED luminaires are reaching reasonable total lumen output levels although many still perceive LEDs as offering only "dim" light, a significant market barrier. OLED packages with useful levels of output remain yet to be developed.
6. Manufacturing: While OLEDs have been built off of display manufacturing capabilities, there has been little investment by manufacturers in the infrastructure needed to develop commercial OLED lighting products. Lack of process uniformity is an important issue for LEDs and is a barrier to reduced costs as well as a problem for uniform quality of light.
7. Codes and Standards: New guidelines for installation, product safety certifications such as the UL provided by the Underwriters Laboratory must be developed. Common standards for fixture (or socket) sizes, electrical supplies and control interfaces may eventually be needed to allow for lamp interchangeability. Standard test methods are still lacking in some areas.

For more information about individual research tasks that address these technical, cost and market barriers, refer to Section 4.5.

4.5. Critical R&D Priorities

In order to achieve these projections, progress must be achieved in several research areas. The original task structure and initial priorities were defined at a workshop in San Diego in February 2005. These priorities were updated in the March 2006 and March 2007 editions of the Multi-year program plan and, because of continuing progress in the technology and better understanding of critical issues, are again revised in this edition of the plan.

With respect to the March 2007 MYPP the following changes in the highest priority tasks have been made for 2008:

For LED Core Technology:

1. Subtask 1.1.3, “Reliability and defect physics for improved emitter lifetime and efficiency,” was removed from the priority list. Significant progress has been reported on chip lifetime, so this is no longer a high priority for investment.

2. Subtask 1.1.1, “Large-area substrates, buffer layers, and wafer research,” was moved to a lower priority. Again, this area of research is at a sufficient state of development that it no longer needs to be among the top core priorities although there is some development work to be done.

3. Subtask 1.2.2 “Strategies for improved light extraction and manipulation” was moved to a lower priority. This task is now largely covered by product development.

4. Subtask 1.3.2 “Encapsulants and Packaging Materials” was moved to the priority list. This task has been somewhat modified to emphasize lower loss and more stable encapsulants and to improve long term reliability of LEDs.

5. Subtask 1.4.x “Inorganic growth, fabrication processes, and manufacturing research” was moved to the priority list. Novel ideas to improve the consistency and uniformity of epitaxial growth and other processes, including improved measurement methods, could reduce the need for binning product and significantly reduce cost. This goes beyond refining existing methods.

For LED Product Development:

1. Subtask 2.3.3, “Power Electronics Development” was moved to the high priority list, but with a more focused scope of work. The lack of small, efficient, high power electronics suitable for converting A.C. line voltage to a suitable current for LED operation limits penetration of LED based products into the direct lamp replacement market and may limit the luminaire lifetime because of the premature failure of some electronic components.

For OLED Core Technology:

1. Subtask 3.1.3, “Improved contact materials and surface modification techniques to improve charge injection” was removed from the priority list. This task is currently at a sufficient state of development to be moved to a lower priority task.

2. Subtask 3.3.2, “Low-cost encapsulation and packaging technology”, was moved to a high priority. An important aspect to improving the performance of an OLED over time is to reduce the sensitivity of organic materials to ambient conditions.

The following tables list the priority tasks for LEDs and for OLEDs for each of Core Technology and Product Development. As in the last edition of the MYPP, there are additional tables listing “later priority” tasks which may ultimately need attention to achieve the overall goals of the program as well as some “long term” research tasks that do not appear to need funding at this time, either because they have reached sufficient advancement, or because they are not immediately necessary to enable progress in the next few years towards SSL goals.

Table 4-6 LED Core Technology Research Tasks and Descriptors (2008-Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Core Technology					
1.1.2	High-efficiency semiconductor materials	Improve IQE across the visible spectrum and in the near UV (down to 360 nm) at high current densities	IQE[12]	20% green (540 nm),75% red, 80% blue	90%
1.3.1	Phosphors and conversion materials	High-efficiency wavelength conversion materials for improved quantum yield, optical efficiency, and color stability	Quantum Yield	95%[13]	90% across the visible spectrum
			Scattering losses	10%	
			Color stability		
1.3.2	Encapsulants and packaging materials	Develop a thermal/photo resistant encapsulant that exhibits long life and has a high refractive index.	Retention of original transmittance[14]		>97%
			Lifetime[15]	50 khrs	
			Refractive Index	1.4-1.57	1.7
1.4.x[16]	Inorganic growth and fabrication processes and manufacturing research.	Novel approaches to improving uniformity and yield for epitaxial growth and other manufacturing processes. Research on diagnostic tools and efficient reactor designs and methods.	Wavelength spread across the wafer	20 nm	5 nm

[12] IQE and EQE status and projections assume pulsed measurements at 350 mA drive currents with a $1x1mm^2$ chip and Tj = 25°C.
[13] Quantum Yield is measured at a pumped wavelength of 450 nm.
[14] Retention should be measured at wavelengths of 450 nm, a flux of $300mW/mm^2$, and Temperature of 185 °C.
[15] Lifetime status and projections are for an encapsulant measured at 185 °C.

Table 4-7: LED Core Technology Research Tasks and Descriptors (Later Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Core Technology					
1.2.1	Device approaches, structures and systems	Alternative emitter geometries and emission mechanisms, i.e. lasing, surface plasmon enhanced emission	EQE	50%	80%
1.2.2	Strategies for improved light extraction and manipulation	Improved chip level extraction efficiency and LED system optical efficiency, including phosphor scattering and encapsulation.	Chip extraction efficiency (χ)	80%[17]	90%
			Phosphor conversion efficiency	80%	90%
1.3.4	Measurement metrics and color perception	Standardizing metrics to measure electrical and photometric characteristics of LED devices.			

Table 4-8: LED Core Technology Research Tasks and Descriptors (Long Term Tasks)

Subtask		Short Descriptor
Core Technology		
1.1.1	Large-area substrates, buffer layers, and wafer research	Develop low cost, high quality substrates that enable epitaxial growth of high quality emitting material
1.1.3	Reliability and defect physics for improved emitter lifetime and efficiency	- Dopant and defect physics - Device characterization and modeling
1.3.3	Electrodes and interconnects	Low resistance electrodes

[16] There are several subtasks to 1.4, designated "x"; all need attention.
[17] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, " Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting," J. Display Technol. 3, 160-175 (2007)

Table 4-9: LED Product Development Tasks and Descriptors (2008-Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
2.2.1	Manufactured materials	**[Phosphor or Encapsulant product]** Develop high efficiency phosphors, luminescent materials, encapsulants, or materials suitable for high-volume, low-cost manufacture, and improved lifetime. Demonstrate improvements in a high-quality packaged prototype chip.	% of original transmission per mm	85-90% (@150C and 10-15kHrs)	95% (@150C Junction Temp. and 50 kHrs)[18]
2.2.2	LED packages and packaging materials	**[Packaged chip or material]** Design and demonstrate a high-quality packaged chip product employing practical, low-cost, designs, materials, or methods for improving light out-coupling and removing heat from the chip to produce a product with high total lumen output efficiently.	Thermal resistance (junction to case)		5ºC per Watt
2.3.1	Optical coupling and modeling	**[Luminaire]** Develop and demonstrate an application-specific luminaire product that solves the problem of extracting useful task-oriented photons from an LED. This task includes addressing issues such as coupling to multiple sources and the multi-shadowing problem.	Optical/Fixture Efficiency	90%	95%
2.3.4	Thermal design	**[Luminaire]** Demonstrate a luminaire or array of LEDs that solves the problem of removing heat from the chip so as to improve luminaire and chip lifetime and reliability.			
2.3.6	Evaluate luminaire lifetime and performance characteristics	**[Luminaire]** Develop and demonstrate a luminaire with significant improvements in lifetime associated with the design methods or materials. Provide extensive characterization to prove the effectiveness of the approach.	Mean time to failure	May be limited by driver lifetime	As good as source lifetimes – >40K hours

[18] This target may change to 185^{o}C as efficiency goals are met and cost becomes a higher priority.

Table 4-9: LED Product Development Tasks and Descriptors (2008-Priority Tasks)(continued)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
2.3.3	Power Electronics Development	**[Modular driver]** Develop a high power modular LED driver capable of converting A.C. line voltage to suitable LED operating currents with low cost, compact size, good power factor, efficient operation, and long lifetime at high operating temperatures.	%Energy Conversion	85%	90+%
			$/Watt	$0.20 /Watt	$0.03 /Watt
			Power factor		0.9
			Lifetime at high operating temperature (125C)	20-50 kHrs[19]	50 kHrs

[19] Some 50 kHr devices exist today, but these are presently for military specifications and are too costly for general illumination applications.

Table 4-10 LED Product Development Tasks and Descriptors (Later Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
2.1.2	High-efficiency semiconductor materials	**[Unpackaged Chip or epitaxial material]** Demonstrate a chip using materials that promote high efficiency across the visible spectrum.	IQE	20% green, 80% red, 60% blue	90%
2.1.3	Implementing strategies for improved light extraction and manipulation	**[Unpackaged Chip, or material]** Apply manufacturable techniques or material products to state-of-the art LEDs to improve light extraction under lighting conditions at low cost.			
2.2.3	Modeling, distribution, and coupling issues	**[Software tool or Luminaire]** Develop models to understand the coupling of the light between the chip and phosphor to optimize the efficiency of the interaction between chip light extraction, phosphor absorption and re-emission, and phosphor scattering. Develop practical techniques to optimize the chip-phosphor coupling and control the resulting optical distribution for various lighting applications			
2.4.1	Incorporate proven in-situ diagnostic tools into existing equipment.	**[Integrated manufacturing measurement tool]** Develop and demonstrate in-situ diagnostic tools into existing equipment to improve manufacturability of LEDs used for lighting.			
2.4.2	Develop low-cost, high-efficiency reactor designs	**[Reactor for low cost manufacture]** Develop and demonstrate growth reactors capable of growing state of the art LED materials at low-cost and high reproducibility with improved materials use efficiency.			
2.4.3	Develop techniques for die separation, chip shaping, and wafer bonding	**[Manufacturing tools]** Develop and demonstrate improved tools and methods for die separation, chip shaping, and wafer bonding for manufacturability.			

Table 4-11 LED Product Development Tasks and Descriptors (Long Term Priority Tasks)

Subtask		Short Descriptor
Product Development		
2.1.1	Substrate, buffer layer and wafer engineering and development	**[Substrate product for chip manufacture]** Develop and demonstrate high quality substrates suitable for improved device efficiency, manufacturing uniformity, and yield.
2.1.4	Device architectures with high power-conversion efficiencies	**[Array of chips]** Demonstrate an array employing large chips, multi-color chips on a single submount suitable for use in a luminaire design.
2.2.4	Evaluate component lifetime and performance characteristics	
2.3.2	Mechanical design	**[Luminaire]** Develop a luminaire mechanical design that contributes to improving energy efficiency through improved optics, thermal management, or any other efficiency factor.
2.3.5	Evaluate human factors and metrics	

Table 4-12 OLED Core Technology Research Tasks and Descriptors (2008-Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Core Technology					
3.1.2, 3.2.2	Novel materials and device architectures.	Single and multi-layered device structures, materials, and contact materials to increase IQE, reduce voltage, and improve device lifetime.	IQE[20]	B>20%, G 100%, R 60%	100% IQE over the visible spectrum
			Voltage	4-5 V	2.8 V
			L_{70}		40,000 hrs
3.2.1	Novel strategies for improved light extraction	Optical and device design for improving light extraction.	Extraction Efficiency	40%	80%
3.2.3	Research on low-cost transparent electrodes	Better transparent electrode technology that offers an improvement over ITO materials cost and deposition rate and shows the potential for low-cost manufacturing.	Ohms/□	40 Ohms/□	<10 Ohms/□
			Transparency over the visible spectrum	75-80%	92%
3.4.2	Investigation of low-cost fabrication and patterning techniques and tools	Development of potentially low cost deposition techniques	Deposition Speed		
			Material utilization		
			Cost/area		
3.3.2	Encapsulation and packaging technology	Demonstrate a high-efficiency OLED luminaire with intrinsically stable OLED materials resilient to the ambient environment or encapsulated or packaged so as to reduce water permeability, improve lifetime, and exhibit the potential for low-cost.	Operating lifetime		40,000 hrs

[20] As noted in Section 4.5.2, these metrics should be measured at a reference brightness of 1000 cd/m^2 and total output ≥ 500 lm.

Table 4-13: OLED Core Technology Research Tasks and Descriptors (Later Priority Tasks)

Subtask		Short Descriptor
Core Technology		
3.1.1	Substrate materials for electro-active organic devices	
3.1.3	Improved contact materials and surface modification techniques to improve charge injection	n- and p- doped polymers and molecular dopants with emphasis on new systems and approaches for balanced charge injection, low voltage, and long lifetime.
3.1.4	Applied Research in OLED devices	Understand the underlying issues limiting performance in organic light emitting devices.
3.3.1	Down conversion materials	
3.3.3	Electrodes and interconnects	
3.3.4	Measurement metrics and human factors	Productivity, preference, and demonstrations; Standards for electrical and photometric measurement
3.4.1	Physical, chemical and optical modeling for fabrication of OLED devices	

Table 4-14: OLED Product Development Research Tasks (2008- Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
4.1.1	Low-cost substrates	**[Substrate Material]** Demonstrate a substrate material that is low cost, shows reduced water permeability, and enables robust device operation.	Cost	~$100/m	< $3/m^2
			Water permeability	10^{-6} g/m^2-day	10^{-6} g/m^2-day
4.1.2, 4.2.2	Practical implementation of materials and device architectures.	**[Device]** Demonstrate an OLED device employing architectures and materials that provide concurrently improve robustness, lifetime, efficiency, and color quality. The device should show potential for mass production.	Efficacy[21]	64 lm/W	>100 lm/W
			CRI	78	90
			Lumen Output	500	5,000
			L_{70}	L_{50}>10 khrs[22]	L_{70}=40 khrs
4.2.1	Practical application of light extraction technology.	**[Device]** Demonstrate an OLED device employing a light extraction technology that features high total extraction efficiency and the potential for large scale manufacturing at low added cost.	Extraction Efficiency	40%	80%
			Cost		
			Lumen Output[23]	500	5,000
4.4.1	Module and process optimization and manufacturing	**[Luminaire]** Produce an OLED luminaire using integrated manufacturing technologies that have a short TAC time and the ability to scale to large areas.	Total Actual Cycle (TAC) time	5 min/m^2	1 min/m^2
4.3.1	OLED encapsulation packaging for lighting applications	**[Luminaire]** Demonstrate a high-efficiency OLED luminaire packaged or encapsulated so as to reduce water permeability and improve lifetime.	$/m^2	$4/m^2	< $3/m^2
			%dark spot area adder		<10% dark spot area adder at 5 year shelf life
			Loss penalty (as compared to glass)		0%
			L_{70}	L_{50}>10 khrs[22]	L_{70}=40 khrs

[21] As noted in Section 4.5.2, efficacy and lumen output should be measured at a reference brightness of 1000cd/m^2 and total output of ≥ 500 lm.
[22] The metric L_{50} is used here because data on L_{70} lifetimes is unavailable.
[23] As noted in Section 4.5.2, lumen output should be measured at a reference brightness of 1000cd/m^2

Table 4-15 OLED Product Development Research Tasks (Later Priority Tasks)

Subtask		Short Descriptor	Metric	2007	2015 Target
Product Development					
4.1.3	Improved contact materials and surface modification techniques to improve charge injection	**[Device]** Develop and demonstrate an OLED device with improved contact materials and surface modification techniques involving n- and p- doped polymers and molecular dopants with emphasis on new systems and approaches for balanced charge injection, low voltage, and long lifetime.			
4.2.3	Demonstrate device architectures: e.g., white-light engines (multi-color versus single emission)	**[Luminaire]** Demonstrate an OLED luminaire employing multi-color chips on a single substrate for use in a luminaire design.			

Table 4-16: OLED Product Development Research Tasks (Long Term Tasks)

Subtask		Short Descriptor
Product Development		
4.3.2	Simulation tools for modeling OLED devices	**[Software Tool]** Develop software simulation tools for modeling performance characteristics of OLED devices.
4.3.3	Voltage conversion, current density and power distribution and driver electronics	**[Driver]** Demonstrate improved drivers for OLED devices with optimized voltage conversion, current density, power distribution, and electronics.
4.3.4	Luminaire design, engineered applications, field tests and demonstrations	**[Luminaire]** Demonstrate in the lab and field-test an OLED luminaire design engineered for a specific application.
4.4.2	Synthesis manufacturing scale-up of active OLED materials	**[Device]** Develop and demonstrate an OLED device using improved materials capable of being scaled-up while maintaining material purity.
4.4.3	Tools for manufacturing the lighting module	**[Manufacturing Tool or Machine]** Demonstrate an improved OLED manufacturing tool or machine.

4.6. Interim Product Goals

To provide some concrete measures of progress for the overall program, the committee identified several milestones that will mark progress over the next ten years. These milestones are not exclusive of the progress graphs shown earlier. Rather, they are "highlighted" targets that reflect significant gains in performance. Where only one metric is targeted in the milestone description, it is assumed that progress on the others is proceeding, but the task priorities are chosen to emphasize the identified milestone.

4.6.1. Light Emitting Diodes

The FY08 LED milestone goal is to produce an LED device product with an efficacy of 80 lm/W, an OEM price of $25/klm (device only), and a life of 50,000 hrs with a CRI greater than 80 and a CCT less than 5000K. These performance characteristics represent a "good" general illumination product that can achieve significant market penetration. These goals have been met individually. In fact, some commercial products have achieved device efficacies greater than 100 lm/W. However, all of the milestone targets have not been met concurrently in a single product. For example, a commercial LED, which has an efficacy of 80 lm/W, is currently priced much higher than $25/klm.

FY10 and FY15 milestones represent efficacy or price targets of LEDs devices with a lifetime of 70,000 hrs. Although all milestones in FY08 were not met concurrently, it is expected that the FY10, interim goal of 140 lm/W for a commercial device will be exceeded. Other parameters will also progress, but the task priorities are set by the goal of reaching this particular mark. A new luminaire milestone has also been included in this update: By FY12, DOE expects to see a high efficiency luminaire on the market that has the equivalent lumen output of a 75W incandescent bulb and an efficiency of 126 lm/W. Finally, by FY15, costs should be below $2/klm for LED devices while also meeting other performance goals.

Table 4-17: LED Product Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	80 lm/W, < $25/klm, 50,000 hrs device
Milestone 2	FY10	> 140 lm/W cool white device; >90 lm/W warm white device
Milestone 3	FY12	126 lm/W luminaire that emits ~1000 lumens
Milestone 4	FY15	< $2/klm device

Assumption: CRI > 80, CCT < 5000°K, $T_j = 125^{o}C$

LED subtasks are shown in four phases of development corresponding to the four milestones. The first phase, essentially complete, is to develop a reasonably efficient white LED device, sufficient to enter the lighting market. Phase 2 is to further improve that efficiency in order to realize the best possible energy savings. This phase should be completed in about two years. Developing a more efficient luminaire is the thrust of

Phase 3, expected to last until about 2012. Finally, the fourth phase is to significantly reduce the cost of LED lighting to the point where it is competitive across the board. This phase, currently underway, is expected to continue past 2015.

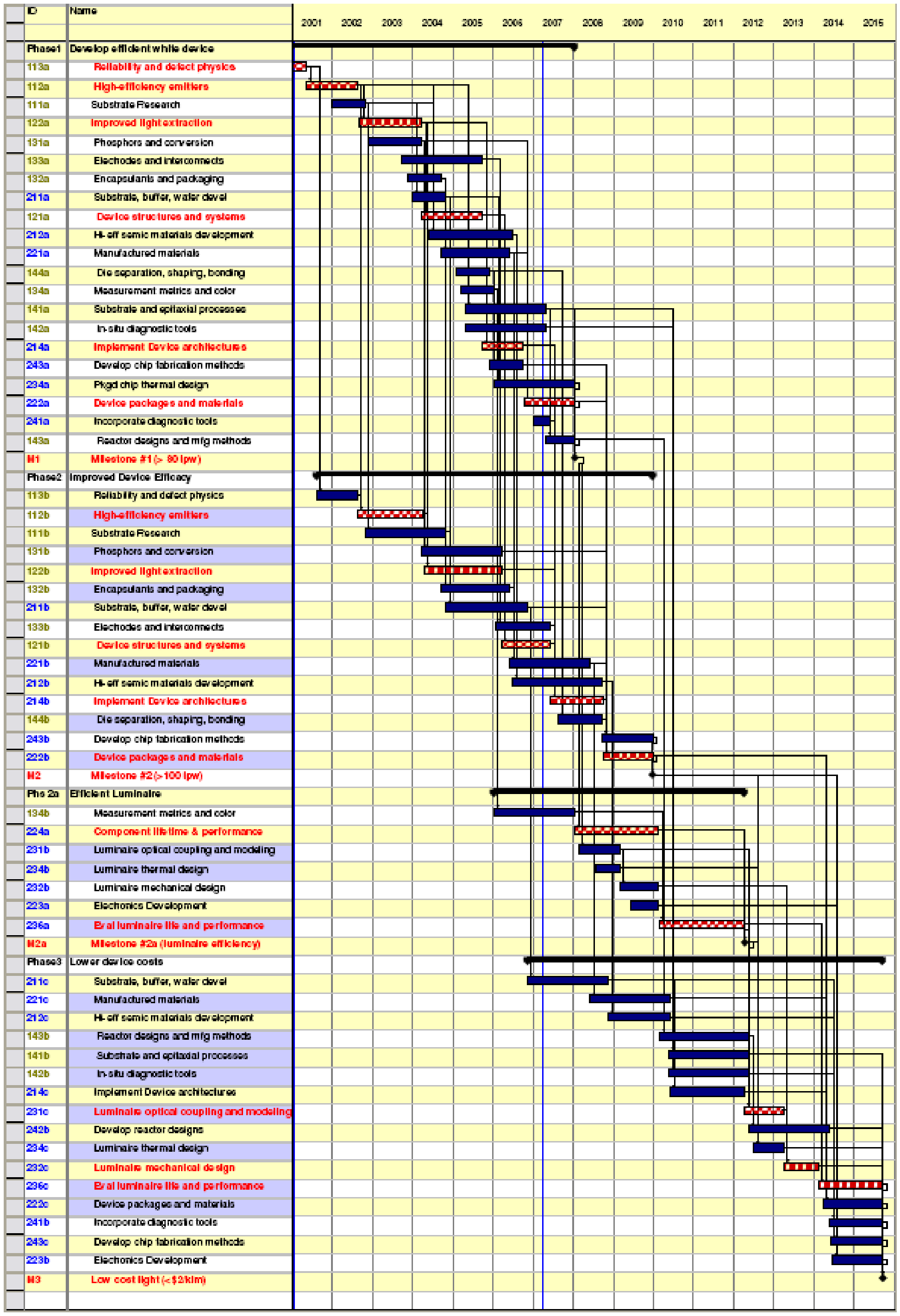
The bars on the Gantt chart indicate an estimated time period for execution of the task in question, while the connecting lines show the interdependence of tasks. The duration of the task depends to some extent on the amount of resources applied. As a deeper understanding of each task is developed, duration estimates can be refined and varied according to the applied resources. Currently, these estimates, based on past experience with funded projects in the DOE program, are approximate. The letters next to the task numbers (a,b,c) identify phases of the tasks. These phases are not to be confused with the overall program phases (1,2,3). Further task phases and program phases will be identified as the program moves past 2015 so that the full potential of solid state lighting can be realized.

Using these estimates of duration and task dependencies, one can identify critical paths to success. Those tasks on the critical path are shown with hashed bars. Tasks identified by the NGLIA/DOE team as high priority have shaded task names. For reasons noted above, the two do not necessarily coincide.

Figure 4-12: White LED Program Gantt Chart

(on page following)

LED Task Phases - Gantt Chart



4.6.2. Organic Light Emitting Diodes

The FY08 OLED milestone is to produce an OLED niche product with an efficacy of 25 lm/W, an OEM price of $100/klm (device only), and a life of 5,000 hrs. CRI should be greater than 80 and the CCT should be between 3,000-4,000K. A luminance of 1000 cd/m^2 and a lumen output greater than 500 lumens should be assumed as a reference level in order to compare the accomplishments of different researchers. That is *not* to say that lighting products may not be designed at higher luminance or higher light output levels.

Although current laboratory devices have reached efficacies between 25 and 64 lm/W (at reasonable life, luminance, and CCT), there are currently no niche OLED products available in the marketplace for general illumination applications. According to industry experts, major manufacturers will wait for OLED laboratory prototypes to achieve higher efficacies before investing in the manufacturing infrastructure to produce OLEDs for general illumination purposes. Therefore, unless a smaller manufacturer, less averse to risk, develops a niche product, the FY08 milestone will not be met. Milestone 2 targets a commercial device efficacy of 50 lm/W by FY10. At this point the lifetime should be around 5,000 hours. Reaching a marketable price for an OLED lighting product, is seen as one of the critical steps to getting this technology into general use because of their large area, so although the FY08 milestone may be late in coming, cost reduction remains the focus. By FY15 the target is to get a high efficacy, 100 lm/W OLED. Cost and lifetime should show continuous improvement as well.

Table 4-18: OLED Product Milestones

Milestone	Year	Milestone Target
Milestone 1	FY08	25 lm/W, < $100/klm, 5,000 hrs
Milestone 2	FY10	<$70/klm
Milestone 3	FY15	>100 lm/W

Assumptions: CRI > 80, CCT < 2700-4100K, luminance = 1,000 cd/m^2, and total output ≥ 500 lumens.
All milestones assume continuing progress in the other overarching parameters - lifetime, and cost.

[The Gantt chart for OLED tasks is still under development but will appear in the final 2008 MYPP.]

4.7 Unaddressed Opportunities

Funding for the research tasks for LEDs and OLEDs is allocated, to the extent possible, according to the priorities agreed upon by the NGLIA and DOE and the annual SSL workshops. These priorities are updated annually, based on actual progress, as described in this document. The task priorities represent estimates at the time of publication as to how best to achieve the program goals, recognizing that there are limits to how much can addressed in any year. This process may leave some critical tasks unfunded at any given time. These obviously represent unaddressed opportunities to accelerate the program or improve performance. This is simply one aspect of managing technology risk, which DOE believes is currently under control.

One area of potential development is to more strongly support improved manufacturing of the products. Though outside the scope of the current program, a development in this area would represent a substantial opportunity for the industry and the country. Several potential benefits of such support are:

- Improved uniformity of processes would improve yields and lower costs.
- Improved control over manufacture would reduce color variation, an impediment to deployment.
- Advanced automation methods could reduce labor content and potentially make domestic production-"made in the USA"- a more attractive option than it is today. Currently most LED chip production has moved to the Far East.
- For OLEDs, the manufacturing issue is particularly acute since the needs for displays, the apparent synergistic technology, are actually quite different from what is needed for lighting. This makes the issue of cost reduction very problematical.

While some manufacturing subtasks are prioritized for core R&D, there is not sufficient funding at this time to support advanced manufacturing development to the extent contemplated above.